Magnetotransport of Ising superconductors

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Summary

In the view of rapid technological development within the past decade and especially approaching the end of Moore's Law era, material science becomes an integral part of the research nowadays. The search for new functional properties and materials which are able to address the challenges of the XXI century is already a daily routine of various research groups and large tech companies around the world. The current library of available 2D materials offers a wide range of properties that can challenge existing 3D technologies. 2D semiconductors, semi-metals, ferromagnets, superconductors and insulators were already identified and are now questioned for being utilized. The top-down and bottom-up approach to synthesize 2D materials provides flexibility to fulfil both scalability and miniaturization for achieving a large number of small devices on-chip. Reduced density of states in two dimensions compared with its 3D parent materials provides a great opportunity to control the electronic properties by means of field-effect doping even in intrinsically metallic materials. The enhanced doping capability of an electric double-layer transistor gives a unique opportunity to unravel the hidden electronic properties and capabilities of materials. For example, turning a band insulator into a superconductor at low temperatures with continuous control of its critical temperature over the entire phase diagram.

Chapter 2 touches another important problem of present days – the search for novel superconducting materials. It has been a long time since people tried to combine both ferromagnetism and superconductivity in single material with the aim to achieve spin-polarized superconductor or even more exotic topological superconductivity. Despite several examples where two order parameters can coexist in heavy fermion compounds, there is a very limited knowledge about this in other systems, where, normally, a small amount of ferromagnetic dopants (1-4%) quenches superconducting order parameter rapidly.

This chapter represents a new milestone achieved ahead of the previous works on field-induced superconductivity. The discovery is naturally about the fundamental physical nature of gate-induced superconductivity, based on intuitive scientific curiosities. This gate-induced phase is the underlying difference that is distinct from other superconducting phases, resulting in unique superconducting properties belonging to layered transition metal dichalcogenides.

This chapter represents a direct and comprehensive answer to those curiosities:

The gate-induced superconducting phase in MoS_2 represents a new type of superconducting phase, called Ising superconductivity. The orientation of spins in a Cooper pair of Ising superconductors is firmly pinned by strong effective Zeeman-type magnetic field. Here, an effective Zeeman field arises from gate-triggered inversion symmetry breaking. Identifying this unique spin configuration in Ising superconductor is the first step towards new properties in Ising superconductors.

Extreme two-dimensionality of gate induced superconducting MoS_2 isolates Ising superconductivity completely from the orbital pair-breaking effect and makes it strongly spin-protected along the out-of-plane direction. Reaching Ising superconductivity also requires subtle interplay between carrier doping, break of inversion symmetry, and spin-orbit interaction by merging core ideas of modern condensed matter physics in a simple system. Field-effect gating uniquely provides those essential ingredients, which is difficult to be accessed by other superconducting systems.

The new understanding of physics in Ising superconductors shed light onto a 40-year-old mystery in understanding unusually high upper critical field found in superconducting transition metal dichalcogenides (TMD) since the 70s. From measurement under high magnetic field up to 37 T, we experimentally showed a huge difference in upper critical field between field-induced and bulk phase, where Ising superconductivity is switched on by breaking of the inversion symmetry using gating. The results point out a unified physical picture for the long-lasting puzzle that lowering of symmetry causes the increase of the upper critical field by unveiling the hidden Ising superconductivity.

Material wise, an emerging family of Ising superconductors is supported by the recent discovery of many TMD superconductors and varieties of choices available from the big class of TMD materials, where a similar mechanism can be readily applied to broaden the horizon in the study of Ising superconductivity.

Chapter 3 represents a milestone in the broad field of two-dimensional (2D) electronics where the science and technology shaping our modern society are based on. For the very first time, we demonstrated that a field-effect device made of a monolayer single crystal – a monolayer of the transition metal dichalcogenide WS_2 - covers a full spectrum of insulator, metal, and superconductor. In particular, to the best of our knowledge, it is the only system where the evolution between a strictly 2D band insulator and 2D superconductor renders a complete dome in a single device. The powerful field effect tuning in a monolayer device opens up a series of surprises that are expected to influence this important field profoundly.

Although 2D field-effect devices have been studied for more than half a century, we just reached a model system that combines a truly 2D system with strong field effect tuning allowing us to access hitherto inaccessible electronic phases and transitions in a single device.

The electronic phases feature a fully developed superconducting dome, which evolves into a surprising re-entrant insulating phase at very strong field-effect gating. The whole spectrum of this complete evolution used to be observed as puzzling pieces without demonstrating a coherent picture. The fully reversible control of the whole spectrum of electronic phase is the best examples to answer the fundamental question of what will exactly happen for gating a monolayer. And the finding is surprising: the final destiny of a gated monolayer is becoming an insulator, which challenges the common belief that higher doping concentration is supposed to be more metallic.

A particular feature of monolayer WS_2 is Ising-type superconductivity due to the valley coupled spin texture. It belongs to a group of unique superconductors that show low transition temperature B_{c2} but ultra-high upper critical field B_{c2} due to various types of spin-protecting mechanisms against an external magnetic field. Comparing with all the strong players in these high B_{c2} superconductors, including previously discovered Ising superconductors such as MoS_2 and $NbSe_2$, WS_2 has clearly set a new record of protection due to larger spin splitting and pure Ising pairing.

The evolution between electronic phases in the complete spectrum settles the recent doubts about the existence of the dome-like superconducting phase diagram. Moreover, it sheds light on many puzzling observations in previous quasi-2D systems, one of which is the dome-like superconducting phase diagrams induced in various band insulators. By observing the fully developed dome and re-entrant insulating phase at high gating in our system, it is clear that the formation of a superconducting dome is due to the subtle interplay of field-effect doping and field-effect localization, which appears ubiquitously in all field-effect devices but can only be clarified unambiguously in truly 2D and strongly tunable system.

Let alone all the scientific importance, from the viewpoint of engineering, highly tunable superconducting transistors made of monolayer crystals are technically promising for nanoelectronics devices. Especially, the present sample is grown by a scalable method of chemical vapour deposition (CVD) making the system an important prototype for the electronic industry.

Chapter 4 addresses the problem of weak screening and interlayer coupling in few-layer WS_2. The effect of field-induced localization at strong gating, discussed in chapter 3 for the case of monolayer device, can be significantly reduced. Extra bottom layers play an important role in screening enhancement and therefore inevitably affecting the superconducting properties via proximity effect. The role of layer number and the effect of interlayer stacking onto its electronic properties was also discussed. Among randomly stacked CVD layers, $2H$ phase showed more promise for an interlayer related physics due to the presence of strongly interacting Q/Q' electron pockets in the vicinity of the conduction band of multilayer TMDs.

Chapter 5. Since the first discovery of Ising superconductivity there were a lot of efforts in this field trying to take advantage of the spin-protected Cooper pair, however, the lack of control over this phenomenon makes this task even more challenging. Here we addressed this problem, as well as broaden our fundamental understanding about Ising superconductivity found in various layered transition metal dichalcogenides.

As far as we know, this is the first coupled superconducting state with strong SOC residing in the neighbouring layers in the thinnest possible limit – freestanding bilayer MoS_2. This is not simply about a new phase diagram where the record-high carrier concentration can be electrostatically induced showing one plus one layer is different from two layers due to the change of band structure. More importantly, the symmetry becomes a truly tunable parameter not only to gets broken but also gets restored by applying an external field effect.

Secondly, present work is a break of a common belief that Josephson interaction is an intrinsic material property. Instead, we demonstrate that it is a dynamic parameter that can be manipulated with the help of external electric fields by changing the doping strength and carrier distribution profile. The upper critical field is the first basic superconducting parameter to be significantly influenced by such kind of change.

To our knowledge, the double-side gated bilayer MoS_2 is the first superconductor that can be tuned below and above the Pauli limit. In other words, the spin-protection of Cooper pair can be manipulated from "ON" to "OFF" in a continuous fashion – which might act as the cornerstone ingredient for exotic superconductivity.